RL-TR-97-243
Final Technical Report
March 1998

GRATING-ASSISTED ALL-OPTICAL SWITCHING IN CdSSe-DOPED NONLINEAR FIBER

University of Connecticut

Sponsored by
Ballistic Missile Defense Organization

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the Ballistic Missile Defense Organization or the U.S. Government.

**AIR FORCE RESEARCH LABORATORY
ROME RESEARCH SITE
ROME, NEW YORK**

This report has been reviewed by the Air Force Research Laboratory, Information Directorate, Public Affairs Office (IFOIPA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

RL-TR-97-243 has been reviewed and is approved for publication.

APPROVED:

ANDREW R. PIRICH
Project Engineer

FOR THE DIRECTOR:

DONALD W. HANSON, Director
Surveillance & Photonics

If your address has changed or if you wish to be removed from the Air Force Research Laboratory mailing list, or if the addressee is no longer employed by your organization, please notify AFRL/SNDP, 26 Electronic Pky, Rome, NY 13441-4514. This will assist us in maintaining a current mailing list.

Do not return copies of this report unless contractual obligations or notices on a specific document require that it be returned.

ALTHOUGH THIS REPORT IS BEING PUBLISHED BY AFRL, THE RESEARCH WAS ACCOMPLISHED BY THE FORMER ROME LABORATORY AND, AS SUCH, APPROVAL SIGNATURES/TITLES REFLECT APPROPRIATE AUTHORITY FOR PUBLICATION AT THAT TIME.

GRATING-ASSISTED ALL-OPTICAL SWITCHING IN CdSSe-DOPED NONLINEAR FIBER

Eric Donkor

Contractor: University of Connecticut
Contract Number: F30602-96-2-0256
Effective Date of Contract: 2 July 1996
Contract Expiration Date: 2 July 1997
Short Title of Work: Grating-Assisted All-Optical Switching in CdSSe-Doped Nonlinear Fiber

Period of Work Covered: Jul 96 - Jul 97

Principal Investigator: Eric Donkor
Phone: (860) 486-3081

AFRL Project Engineer: Andrew R. Pirich
Phone: (315) 330-4147

Approved for public release; distribution unlimited.

This research was supported by the Ballistic Missile Defense Organization of the Department of Defense and was monitored by Andrew R. Pirich, Air Force Research Laboratory/SNDP, 26 Electronic Pky, Rome, NY 13441-4514.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
March 1998

3. REPORT TYPE AND DATES COVERED
Final Jul 96 - Jul 97

4. TITLE AND SUBTITLE
GRATING-ASSISTED ALL-OPTICAL SWITCHING IN CdSSe-DOPED NONLINEAR FIBER

5. FUNDING NUMBERS
C - F30602-96-2-0256
PE - 61102F
PR - 2300
TA - 05
WU - P2

6. AUTHOR(S)
Eric Donkor

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Connecticut
438 Whitney Road Extension
Storrs CT 06269-1133

8. PERFORMING ORGANIZATION REPORT NUMBER
N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Ballistic Missile Defense Organization/TRI
7100 Defense Pentagon
Washington DC 20301-7100

Air Force Research Laboratory/SNDP
26 Electronic Pky
Rome NY 13441-4514

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
RL-TR-97-243

11. SUPPLEMENTARY NOTES
Air Force Research Laboratory Project Engineer: Andrew R. Pirich/SNDP/(315) 330-4147

12a. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
Three experiments were performed during this effort. The first experiment measured the pump induced wavelength shift of a 1550 nm probe signal in a 100 cm CdSSe doped fiber. This initial experiment provided the necessary data which formed the basis for the design of a new all-optical switch. The second experiment was the fabrication of the all-optical switch. The operation of the switch was based upon the pump-induced wavelength shift of a probe signal. The presumption that such a switch could be designed to be more stable and have higher contract ratios than a Mach-Zehnder switch or "loop-mirror" all-optical switches was demonstrated. In the process of conducting this work, a design configuration for a three-terminal optical gate was developed. The best on-off switching time was 70 ps. The third experiment determined the transfer characteristics of the optical gate. The transfer characteristics exhibited similar current-voltage characteristics to an electronic transistor; a basic building-block for designing all-optical logic gates.

14. SUBJECT TERMS
'All-Optical' Switches, Optical Gate, 'Optical' Transistor, CdSSe Doped Fiber

15. NUMBER OF PAGES
28

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

A. Technical Summary

This report summarizes a one-year project, the purpose of which is to design an all-optical switch that uses CdSSe-doped fibe as the switching medium. The "Statement of Work" for the project is to:

1) Measure and provide experimental data for the amount of wavelength shift that can be realized in a 1550 nm probe signal using a 1313 nm pump signal in a CdSSe-doped Kerr fiber.
2) Implement a prototype optical switch whose operation is based on the phenomena of pump induced wavelength shift and to demonstrate the operation of the device at diode power levels.
3) Characterize the performance of the switch in terms of contrast ratio, switching power as a function of device length and optimum switching speed, and determine the Bit-Error-Rate performance of the switch.

Three main experiments were performed. The first experiment was designed to measure the pump (1319 nm) induced wavelength shift of a 1550 nm probe signal in a 100 cm of CdSSe-doped fiber. This initial experiment was designed to provide data and information that would form the basis for the design and implementation of an all-optical switch. The second experiment was the design and characterization of an all-optical switch. The operation of the switch was based upon pump-induced wavelength shift of a probe. The presumption was that such a switch could be designed to be more stable and have higher contrast ratio than interferometric, i.e. Mach-Zehnder switches, or loop-mirror all-optical switches.

In the process of conducting this work, we incidentally discovered a design configuration for a three-terminal optical gate with transfer characteristics similar to the current-voltage characteristics of an electronic transistor. The third experiment describes the design and measurement of the transfer characteristics of the optical gate.

The CdSSe-doped glass fiber was commercially produced by Collimated Holes Inc. The linear and nonlinear properties of the fiber had previously been characterized. The linear characteristics included measurement of the transmittance and absorption coefficient. The transmittance was measured for wavelength ranging between 300 nm and 1800 nm, and the absorption coefficient of the fiber was measured and found to be 0.14 dB/cm. The nonlinear refractive index of the fiber was also measured and found to be 1.8 x 10^{-17} W/cm^2 at 1319 nm. This value of the nonlinear refractive index was about 400 times higher than ordinary class.

We have presented portions of our work at technical conferences and published pertinent results in two conference proceedings.

B. Measurement of Induced wavelength Shift In CdSSe-Doped fiber.

The first experiment we performed was designed to measure the induced wavelength shift of a 1550 nm probe by a 1319 nm pump. A CdSSe-doped fiber served as a Kerr nonlinear medium for the pump-probe interaction. Results of this experiment was valuable in determining the criteria needed to design and implement the optical switch. The experimental set up is as shown in figure 1.

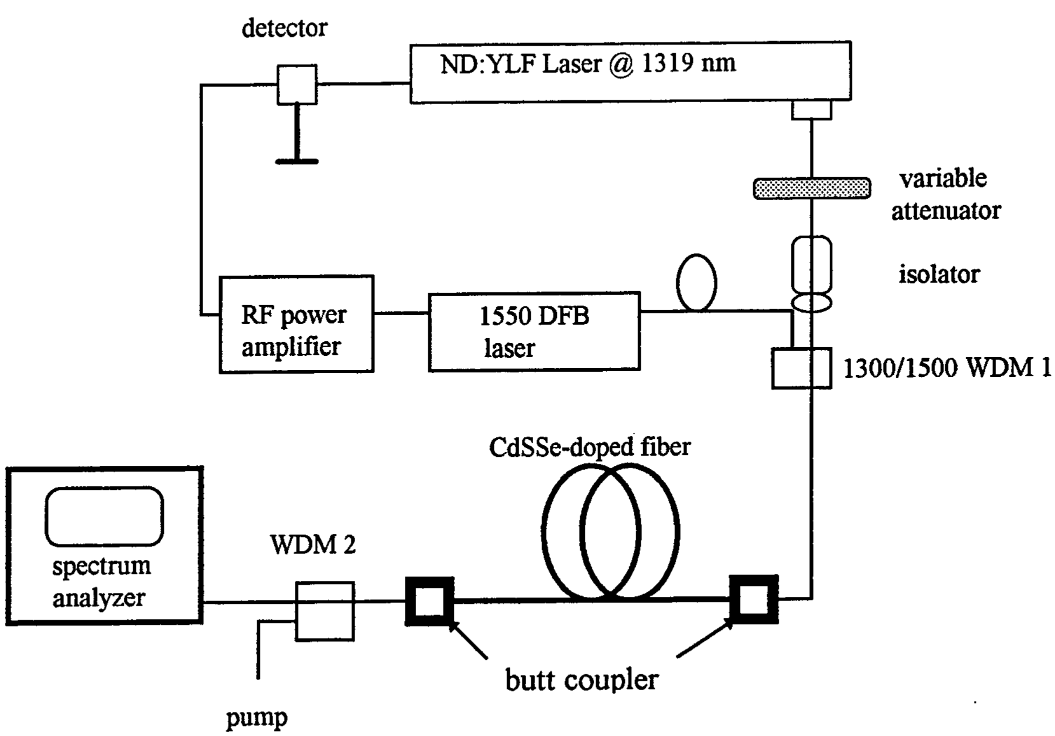


Fig. 1 Setup for measurement of 1319 nm pump-induced wavelength shift of a 1550 nm probe.

The pump was a Quantronix ND:YLF pulsed laser with emission wavelength of 1319 nm. The output pulses of the laser varied between 70 to 90 ps, with a pulse repetition rate of 100 Mhz. A variable attenuator was used to control the amount of pump power coupled

into the fiber. An isolator was also introduced in the path of the pump to safe guard the laser against back reflections. The probe signal was a cw 1550 nm distributed-feedback (DFB) laser. The laser was gain switched to produce 70-90 ps pulses with a repetition rate of 100 Mhz. To gain switch the DFB laser, a fraction of the pump signal was tapped-off and directed unto a 20 Ghz detector. The detected signal was amplifier, by the RF power amplifier, and the amplified signal used to gain switch the DFB laser.

The pump and probe pulses were coupled into the CdSSe-doped fiber via a 2x1 1330/1550 nm wavelength division multiplier (WDM 1). The output of the WDM 1 was butt-coupled to one end of the CdSSe-doped fiber. The length of fiber used was 100 cm. Another 1330/1550 nm wavelength-division demultiplexer, WDM 2, was butt-coupled to the other end of the fiber. Finally, the output of the WDM 2 was connected to the spectrum analyzer.

Figure 2 shows a gain-switched 1550 nm pulse through the fiber in the presence of a pump pulse. A pump induced wavelength shift of between 0.1 - 0.3 nm was measured.

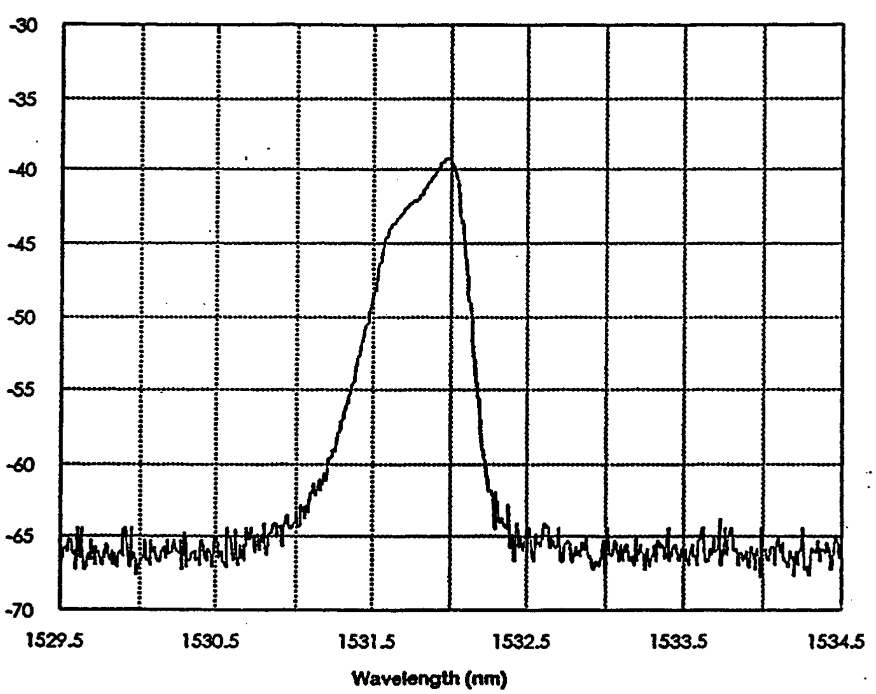


Fig. 2 Gain switch 1550 nm probe signal through CdSSe-doped fiber.

This was lower than the theoretically calculated wavelength shift of 1 nm according to the following formula:

$$\Delta\lambda_{probe} = -\frac{2\lambda^2_{probe} n_2}{c\lambda_{pump} A_{eff}} P_p \frac{L_W}{T_o}$$

Here, λ_{probe}, and λ_{pump}, are the probe and pump wavelengths respectively. The non-linear refractive index of the CdSSe-doped fiber is n_2, P_p- is the peak pump power; L_w- is the walk-off length between the pump and probe, T_o- is the pulse-width which was taken as 2 ps, A_{eff}- is the effective area of the fiber, and c is the speed of light.

The failure to measure an appreciable pump induced wavelength shift of the probe was attributed to:

1) Wide pulse-width of pump and probe.

The pulse-width of the pump and the probe pulses used in the theoretical calculation was 2 ps. but the pulse-width of the pump and probe were between 70-90 ps. We attempted to compress the 70 ps pulses down to 2 ps, but was unsuccessful.

2) Pump absorption by the CdSSe-doped fiber.

Because of the relatively high loss of the CdSSe-doped fiber, 0.14 dB/cm, pump absorption in the 100 cm long fiber was significant. This meant that the pump-induced phase shift of the probe signal would be significantly lower. Since the wavelength shift is defined to be the time derivative of the phase shift, the low phase shift translated into a small wavelength shift for the probe.

3) Jitter of Pump Signal.

The pump pulses were found to fluctuate or jitter. This caused a large walk-off between the pump and probe thereby reducing the interaction time of the pump and probe signals in the CdSSe-doped fiber.

C. All-optical switching In A CdSSe-doped Glass/ZnSe composite Structure.

To alleviate the problems indicated above we redesigned the switch configuration. The main features of the new design included: 1) the use of a stable cw Argon laser as the pump. Pump pulses were generated from the cw laser by mechanically chopping the output signal, 2) the operation of the all-optical switching structure did not require short pulses, and 3) an active medium consisting of a composite of CdSSe-doped glass and amorphous ZnSe. The thickness of the CdSSe-doped glass was 3-mm and of the ZnSe was 2 mm. Thus the total length of the switch was only 5 mm.

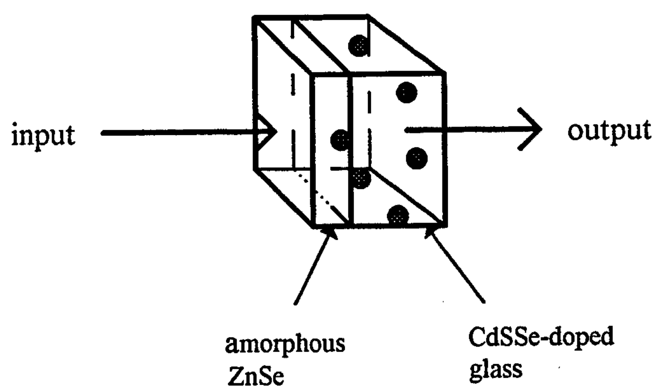


Fig. 3 ZnSe/CdSSe-doped glass composite used as active medium for all-optical switching.

The 2 mm ZnSe sample was polished on opposite surfaces. The CdSSe-doped glass was purchased from Schott glass as a 3 mm RG 630 sample with its surfaces already polished. The fractional composition of the CdSSe in the RG 630 is about 1%. Also the molar fraction of the selenium in the tertiary $CdS_x Se_{1-x}$ is x = 0.5. The composite was formed by gluing the ZnSe and the CdSSe-doped glass tightly together along the contact edges. The

ZnSe outer surface was designated as the input, and the outer surface of the CdSSe-doped glass was designated as the output of the device. The refractive indices of the CdSSe-doped glass and the ZnSe were 1.55 and 2.2 respectively. Thus the composite structure acted as a non-linear grating element.

An all-optical switching configuration using the non-linear grating element is shown in figure 4. The pump is a 500 nm cw argon laser. A mechanical chopper was

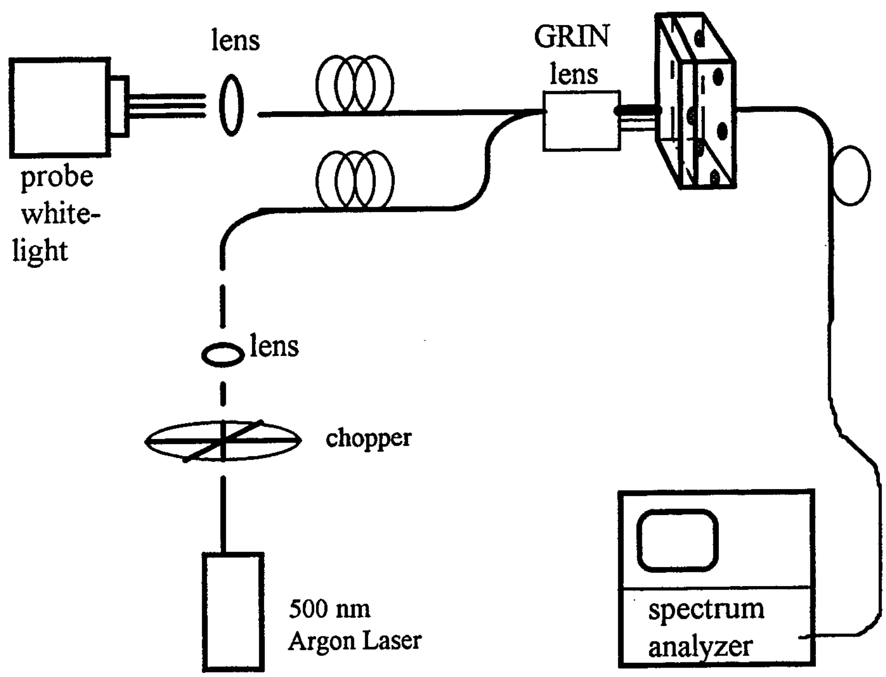


Figure 4. All-optical switching in CdSSe-doped glass/ amorphous ZnSe composite. The pump is a chopped 500 nm Argon Laser. A white light source was used to demonstrate the versatility of the switch to operate at a wide range of frequencies.

introduced in the path of the pump beam to generate pump pulses. The pulse rate was 1Khz. The pump pulses were couple unto a multi-mode optical fiber. A white light source was used as the probe. The purpose of using white light was to demonstrate the capability of the switch to operate at different wavelengths and also to show that the switch is polarization insensitive. The white light was also coupled unto another

multimode fiber. The other ends of the coupling fibers for the pump and probe were butt-coupled to a GRIN lens. The nonlinear element was placed behind the GRIN lens, with the

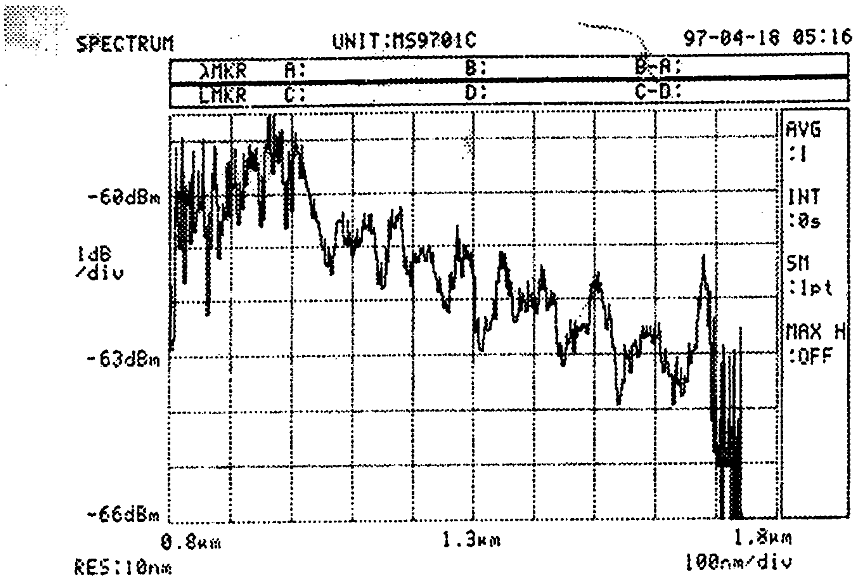


Fig. 5a. Transmittance of white light (probe) through nonlinear element with the pump off.

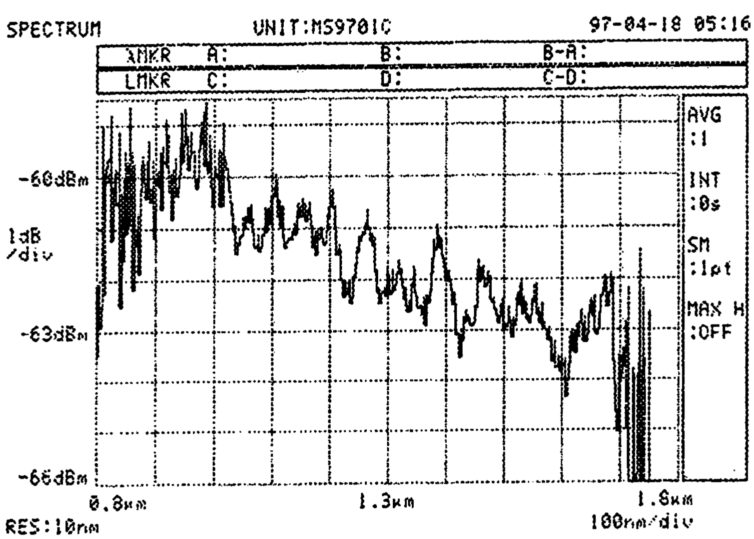


Fig. 5b. Transmittance of white light (probe) through nonlinear element with the pump ON.

ZnSe face, closer to the lens. The output was coupled into a multi-mode fiber, and the other end of the output fiber connected to an optical spectrum analyzer.

Figure 5a, shows the transmittivity of the white light source through the non-linear device as measured by the experimental set-up of figure 4, with the pump signal turned-off. Figure 5b depicts the transmittance of the white-light source through the non-linear devices in the presence of the pump signal. The most striking feature of figures 5a and 5b is the periodicity of the transmittance of the white light through the CdSSe-doped glass/ZnSe nolinearity element with and without the pump. Furthermore, we notice that the peaks in figure 5a and 5b are inverted relative to each other. For example in figure 5a, a high peak is observed at 1680 nm, but in figure 5b a low peak, or valley, is observed at the 1680 nm. As a second example in figure 5a, a valley is shown at 1100nm, but in figure 5b a peak is observed at 1100nm. Thus the effect of the pump corresponds to a complete switching of the probe signals through the nonlinear devices.

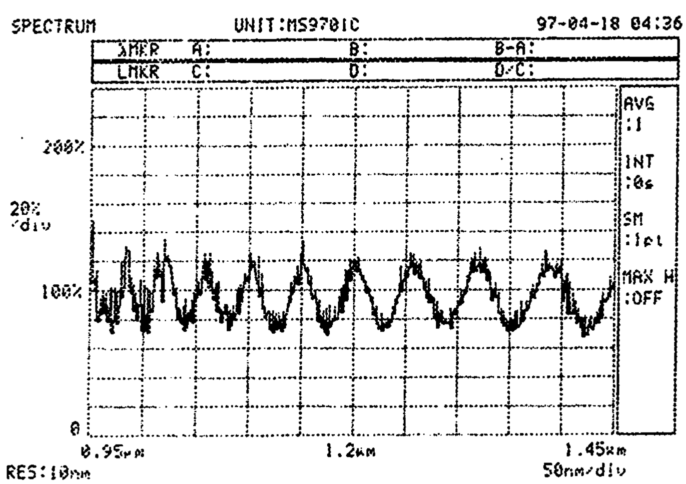


Fig. 6. Subtraction of figure 5a from fig 5b.

Figure 6 is the result obtained by subtracting figure 5a from figure 5b using the difference function of the spectrum analyzer. The figure shows a distinctive period function. The peak-to-peak amplitude remains constant for all wavelengths. The

difference between adjacent maximum-to-minimum peaks corresponds to the wavelength shift produced by the pump. For instance the pump induced wavelength shift is 50 nm at 1300 nm. The pump power used was 500 mW.

The figure also indicates preferred wavelengths for which the device can operate. These wavelengths depend both on pump power and the geometry of the devices. The switch can therefore be designed to operated optimally at any given wavelength, within the transmittance spectra of the nonlinear ZnSe/CdSSe-doped glass composite structure.

A practical implementation of the switch will have to include a wavelength filter element, such as a fiber grating , at the output. If such a filter is designed to have high transmittance at the signal wavelength, and the ZnSe/CdSSe-doped glass element is also designed for optimal operation at the same signal wavelength, then maximum transmittance will be obtained for the probe signals. This then will correspond to the "ON" state of the switch. If a pump is applied, such that there is a shift in the probe wavelength greater than the bandwidth of the filter, then the resulting shift in wavelength of the probe causes the probe signal to be reflected by the grating. This corresponds to the "OFF-state" of the switch. Thus the switch characteristics will depend largely on the design of the grating.

C. A Three-Terminal Optical Gate

In the course of doing this work we discovered a three-terminal optical gate that exhibited transfer characteristics similarly to the current-voltage characteristics of an electronic transistor. Such a three terminal gate can be the basic building block for designing all-optical logic gates.

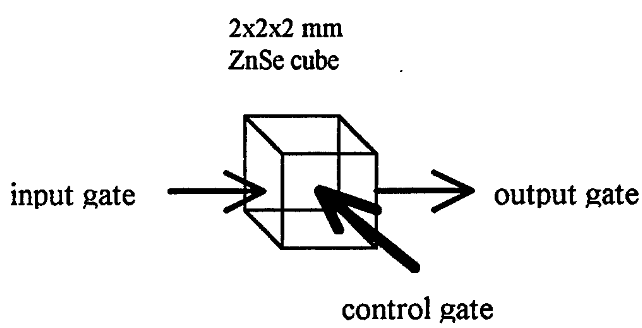


Figure 7. A three-terminal all-optical gate

The three-terminal optical gate is a 2 x2x2 mm ZnSe cube with all six surfaces polished. Two opposite surfaces were designated input and output gates. The side of the ZnSe adjacent to both the input and output faces was designated as the control gate as shown in figure 7.

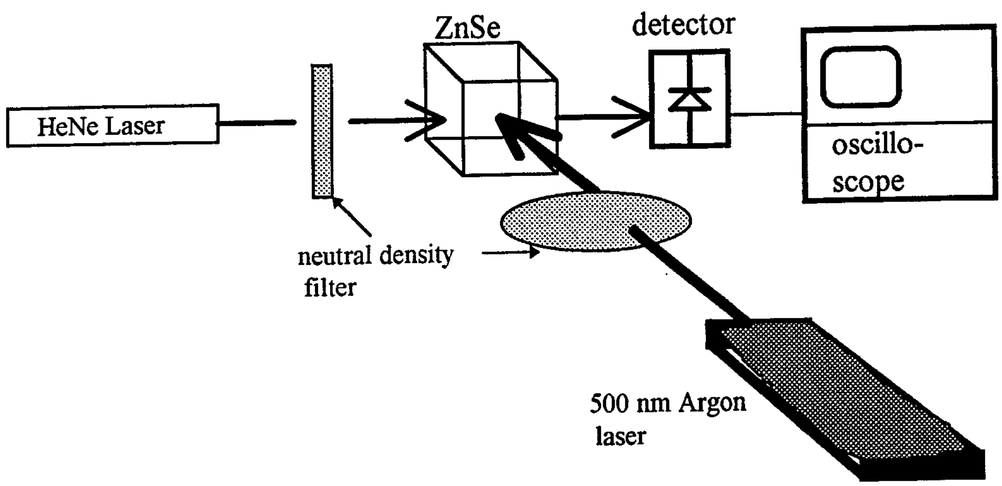


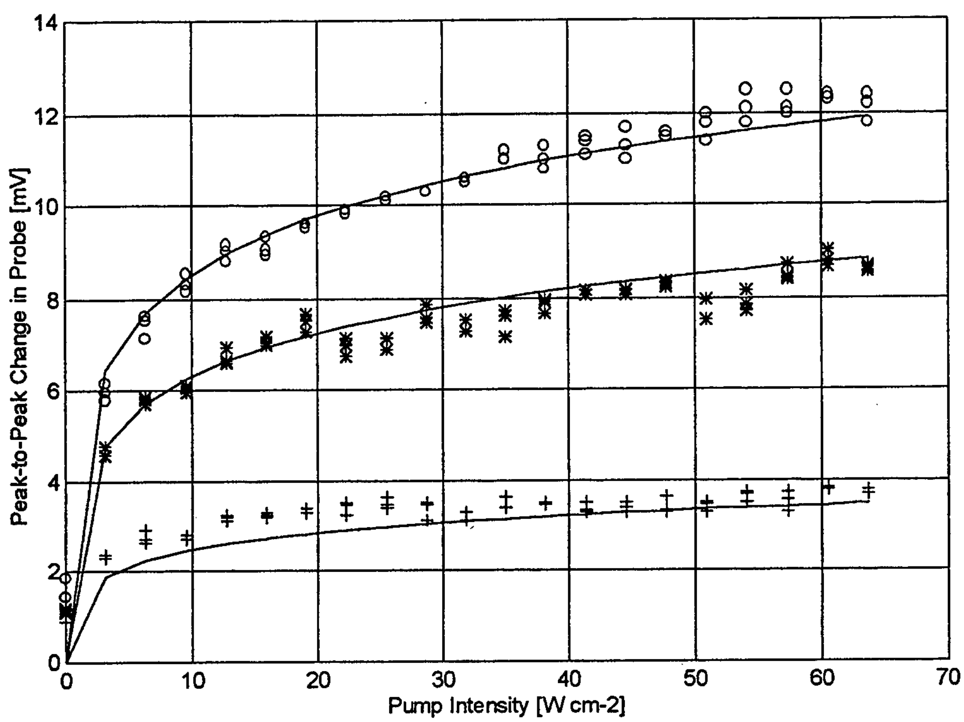
Fig. 8 Experimental setup for measuring the transfer characteristics of the optical gate.

The experimental setup for measuring the transfer characteristics of the optical gate is shown in figure 8. A cw HeNe laser was used as the probe signals, and a cw 500 nm Argon laser was used as the control signal. Neutral density filters were inserted in the probe and control signals to control the respective optical power reaching the gate. The output of the gate was detected by a power meter which in turn was connected to an oscilloscope. The detector output voltage, displayed on the oscilloscope, was measured as a function of the control power from the Argon laser, with the input power from the HeNe as parameter.

A sketch of the output transfer characteristics of the optical gate is depicted in figure 9. The three curves represent input power of 1.7 mW (bottom curve), 4.3 mW (middle curve), and 5.8 mW (upper curve). The pump intensity was varied from 0-65 W cm^{-2}. As depicted in figure 9, the transfer characteristics of the optical gate has features

similar to an electronic transistor. That is, the characteristics of the gate has a linear region, a knee region, and a saturation region.

Considering the low pump intensities, the simplicity of the gate and the well behaved transfer characteristics, we believe that this device can form the building block for all-optical logic gates, needed for all-optical computing.



o => Probe Power 5.8 mW

* => Probe Power 4.3 mW

+ => Probe Power 1.7 mW

Fig. 9 Transfer characteristics of an all- optical gate.

In conclusion, we have fabricated an all-optical switch that operates on the phenomena of pump-induced wavelength shift of a probe signal. The enabling technology was the design of a ZnSe/CdSSe-doped glass composite nonlinear element. This devices could be used in implementing all-optical switching required in communication. We also

designed and characterized a three-terminal all optical gate that exhibited (electronic) transistor-like transfer characteristics. The gate could be an important device~~s~~ as the building block for implementing all-optical logic gates.

DISTRIBUTION LIST

addresses	number of copies
ANDREW R. PIRICH ROME LABORATORY/OCPA 25 ELECTRONIC PKY ROME NY 13441-4515	1
ERIC DONKOR UNIVERSITY OF CONNECTICUT 438 WHITNEY ROAD EXTENSION STORRS CT 06269-1133	1
ROME LABORATORY/SUL TECHNICAL LIBRARY 26 ELECTRONIC PKY ROME NY 13441-4514	1
ATTENTION: DTIC-OCC DEFENSE TECHNICAL INFO CENTER 8725 JOHN J. KINGMAN ROAD, STE 0944 FT. BELVOIR, VA 22060-6218	2
BALLISTIC MISSILE DEFENSE ORGANIZATION 7100 DEFENSE PENTAGON WASH DC 20301-7100	2
RELIABILITY ANALYSIS CENTER 201 MILL ST. ROME NY 13440-8200	1
ATTN: GWEN NGUYEN GIDEP P.O. BOX 8000 CORONA CA 91718-8000	1
AFIT ACADEMIC LIBRARY/LDEE 2950 P STREET AREA B, BLDG 642 WRIGHT-PATTERSON AFB OH 45433-7765	1

ATTN: R.L. DENISON 1
WRIGHT LABORATORY/MLPO, BLDG. 651
3005 P STREET, STE 6
WRIGHT-PATTERSON AFB OH 45433-7707

WRIGHT LABORATORY/MTM, BLDG 653 1
2977 P STREET, STE 6
WRIGHT-PATTERSON AFB OH 45433-7739

WRIGHT LABORATORY/FIVS/SURVIAC 1
2130 EIGHTH STREET, BLDG 45, STE 1
WRIGHT-PATTERSON AFB OH 45433-7542

ATTN: GILBERT G. KUPERMAN 1
AL/CFHI, BLDG. 248
2255 H STREET
WRIGHT-PATTERSON AFB OH 45433-7022

AIR UNIVERSITY LIBRARY (AUL/LSAD) 1
600 CHENNAULT CIRCLE
MAXWELL AFB AL 36112-6424

US ARMY SSDC 1
P.O. BOX 1500
ATTN: CSSD-IM-PA
HUNTSVILLE AL 35807-3801

COMMANDING OFFICER 1
NCCOSC RDT&E DIVISION
ATTN: TECHNICAL LIBRARY,CODE D0274
53560 HULL STREET
SAN DIEGO CA 92152-5001

NAVAL AIR WARFARE CENTER 1
WEAPONS DIVISION
CODE 48L000D
1 ADMINISTRATION CIRCLE
CHINA LAKE CA 93555-6100

SPACE & NAVAL WARFARE SYSTEMS CMD 2
ATTN: PMW163-1 (R. SKIANO)RM 1044A
53560 HULL ST.
SAN DIEGO, CA 92152-5002

SPACE & NAVAL WARFARE SYSTEMS COMMAND, EXECUTIVE DIRECTOR (PD13A) 1
ATTN: MR. CARL ANDRIANI
2451 CRYSTAL DRIVE
ARLINGTON VA 22245-5200

COMMANDER, SPACE & NAVAL WARFARE SYSTEMS COMMAND (CODE 32) 1
2451 CRYSTAL DRIVE
ARLINGTON VA 22245-5200

CDR, US ARMY MISSILE COMMAND 2
REDSTONE SCIENTIFIC INFORMATION CTR
ATTN: AMSMI-RD-CS-R, DOCS
REDSTONE ARSENAL AL 35898-5241

ADVISORY GROUP ON ELECTRON DEVICES 1
SUITE 500
1745 JEFFERSON DAVIS HIGHWAY
ARLINGTON VA 22202

REPORT COLLECTION, CIC-14 1
MS P364
LOS ALAMOS NATIONAL LABORATORY
LOS ALAMOS NM 87545

AEDC LIBRARY 1
TECHNICAL REPORTS FILE
100 KINDEL DRIVE, SUITE C211
ARNOLD AFB TN 37389-3211

COMMANDER 1
USAISC
ASHC-IMD-L, BLDG 61801
FT HUACHUCA AZ 85613-5000

US DEPT OF TRANSPORTATION LIBRARY 1
FB10A, M-457, RM 930
800 INDEPENDENCE AVE, SW
WASH DC 22591

AFIWC/MSY 1
102 HALL BLVD, STE 315
SAN ANTONIO TX 78243-7016

NSA/CSS 1
K1
FT MEADE MD 20755-6000

PHILLIPS LABORATORY 1
PL/TL (LIBRARY)
5 WRIGHT STREET
HANSCOM AFB MA 01731-3004

ATTN: EILEEN LADUKE/D460 1
MITRE CORPORATION
202 BURLINGTON RD
BEDFORD MA 01730

OUSD(P)/DTSA/DUTD 2
ATTN: PATRICK G. SULLIVAN, JR.
400 ARMY NAVY DRIVE
SUITE 300
ARLINGTON VA 22202

ROME LABORATORY/ERO 1
ATTN: RICHARD PAYNE
HANSCOM AFB, MA 01731-5000

ROME LABORATORY/EROC 1
ATTN: JOSEPH P. LORENZO, JR.
HANSCOM AFB, MA 01731-5000

ROME LABORATORY/EROP 1
ATTN: JOSEPH L. HORNER
HANSCOM AFB, MA 01731-5000

ROME LABORATORY/EROC 1
ATTN: RICHARD A. SOREF
HANSCOM AFB, MA 01731-5000

ROME LABORATORY/ERXE 1
ATTN: JOHN J. LARKIN
HANSCOM AFB, MA 01731-5000

ROME LABORATORY/ERDR 1
ATTN: DANIEL J. BURNS
525 BROOKS RD
ROME NY 13441-4505

ROME LABORATORY/IRAP 1
ATTN: ALBERT A. JAMBERDINO
32 HANGAR RD
ROME NY 13441-4114

ROME LABORATORY/C3BC 1
ATTN: ROBERT L. KAMINSKI
525 BROOKS RD
ROME NY 13441-4505

ROME LABORATORY/OCP 1
ATTN: MAJOR GARY D. BARMORE
25 ELECTRONIC PKY
ROME NY 13441-4515

ROME LABORATORY/OCP 1
ATTN: JOANNE L. ROSSI
25 ELECTRONIC PKY
ROME NY 13441-4515

NY PHOTONIC DEVELOPMENT CORP 1
MVCC ROME CAMPUS
UPPER FLOYD AVE
ROME, NY 13440